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Off-grid desalination for irrigation in the Jordan Valley

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ABSTRACT

Groundwater resources in many regions of the world are becoming increasingly depleted and salinized. With many aquifers straddling political boundaries, on-going depletion presents both a flashpoint for conflict and an opportunity for cooperation. A salient example is that of transboundary groundwater resources in the Jordan Valley. These are shared among Israeli, Jordanian and Palestinian residents. Here we describe a collaborative project aiming to develop a desalination system for use by Palestinian farmers in the West Bank. Students have collaborated across borders in a programme of training and research, in which they have constructed desalination prototypes. These are based on a simple but efficient batch-reverse osmosis (RO) technology that incorporates energy recovery and brine recirculation to achieve 70%–76% recovery and specific energy consumption <1.3 kWh/m^3. The technology can be solar powered with minimal PV footprint. Being built almost entirely from off-the-shelf parts, the system is readily implemented with levels of engineering expertise available in many areas of the world. To test and upscale the technology, and to propagate the knowledge about it, it is being trialled at centres in the UK, Israel and soon in Palestine. It is concluded that the project demonstrates a valuable approach in regions facing transboundary groundwater challenges, and that further learning resources should be developed for free access to foster collaboration across borders.

Keywords: Groundwater; Solar PV; Batch-RO; High recovery; Transboundary resources; Regional cooperation

1. Introduction

There are several instances where effective management of water resources necessitates cross-boundary cooperation. Hydrological resources are not naturally subject to political boundaries. Rivers flow between countries; and aquifers straddle international and territorial borders. With population growth, climate change and depletion of conventional water resources, the need for cooperative approaches is ever more important in the management of transboundary water resources.

This paper focuses on the Jordan Valley, where groundwater resources are shared among Israeli, Jordanian and Palestinian neighbours. We describe a project that sets out to provide: (i) a training programme for students and, in parallel, (ii) a research programme executed by the students. The overall aim is to develop an affordable off-grid desalination technology for on-site use by farmers to improve

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brackish water for irrigation in the Jordan Valley. At the outset of the project, specific objectives with regard to training and research were defined as follows. The training objectives were as follows:

- To provide a scientific forum for students from UK, Israel and Palestine to collaborate in tackling a common water challenge.
- The project and technology must involve community participation and training to ensure long-term sustainability.
- The designs and instructions should be made freely available via the internet for use across MENA.

The research objectives were concerned with developing desalination technology with high recovery and high efficiency. A series of prototypes were to be developed, that should:

- Be suitable for off-grid operation using solar photovoltaic energy.
- Achieve recovery ratio > 75%, for minimum brine discharge.
- Give outputs in the range 2–4 m^3/d, with prospects to scale up to 100 m^3/d.
- Be made from readily available parts for ease of replication.

The outline of the paper is as follows. We begin by reviewing the status of groundwater resources in the Jordan Valley. We then outline the relevant political background, going on to introduce the opportunities and challenges for cooperation. This is followed by a description of the training programme, and then by a report on the progress of the research and technology development associated with this training. We evaluate the experience so far, and reflect on future directions to improve the student experience and technological achievement in this on-going project.

2. Background

2.1. Groundwater resources in the Jordan Valley

Palestine has two main water resources, surface water and ground water. The surface water of the river Jordan is fully exploited by Israel, Jordan, Syria and Lebanon, such that no surface water from the river is available to Palestine. Groundwater is the second most important water resource in Palestine and Israel. Out of nine aquifers, four are located to a large extent in the West Bank (Fig. 1). The Eastern Aquifer is one of the most important ground water basins which runs along the eastern half of the West Bank, where Palestinians take advantage of 40% of it, while Israelis take advantage of the remaining 60% since the occupation of the West Bank in 1967 [1]. The Jordan Valley is situated over the Eastern Groundwater Basin and, together with the northern Dead Sea area, makes up approximately 30% of the West Bank and includes the most significant Palestinian land reserves. The Jordan Valley area is home to 60,000 Palestinians, half of whom live in the Jericho area and cultivate 5,300 hectares of land [2].

The lower Jordan valley depends exclusively on groundwater for agricultural irrigation from the Eastern Mountain aquifer [3]. Irrigated agriculture makes up one third of total agricultural production in the West Bank, and uses 52% of the water resources. Increase in both population and water shortages is leading to over exploitation of groundwater [4]. The water quality of the Jordan Valley has been deteriorating with increasing salinization. For example, in the Jericho region, chloride concentrations in the groundwater, being a proxy for salinity, have increased to >2,000 mg/L over the last 30 years [3].

Record highs of water salinity levels are leading to changes in cropping patterns. Cash crops which are intolerant to salinity have been replaced by 250,000 Medjool date palms, 50,000 of which are older than 5 years [5]. Considering that a Medjool date palm tree older than 5 years requires a 100 m^3 of water per year, and the capacity of the shallow aquifer is 11,000,000 m^3/year, we can see that a negative water balance will occur within 5 years. Date palms are salt tolerant yet less profitable than many cash crops, and the loss of biodiversity associated with cultivating only date palms can lead to disease of the palms. Desalination of the saline shallow water aquifer will allow farmers to return to the historically cultivated cash crops with less stress on water resources and will provide economies of scale for farmers.

2.2. Opportunities and challenges for cooperation

Current water use in the West Bank is mainly established in the Oslo II accords, an agreement signed by Israel and the PLO in 1995. Article 40 states that the purpose of the agreement is to prevent water quality deterioration and manage water sustainably for future use. The Article also allots 70–80 million m^3/year (MCM/year) to Palestinian water needs in the West Bank [6]. To ensure correct process, Schedule 8 determines that a Joint Water Committee (JWC) be formed to coordinate management of water resources and sewage. The JWC, which must have equal representation of Israelis and Palestinians, provides approval for new water developments including well drilling, licensing, water extraction, and system development. They oversee development of a protocol for supplying water across boundaries, and form the following subcommittees: technical, price, legal and water/wastewater [7]. Further, Joint Supervision and Enforcement Teams (JSETs) are to be formed with the purpose of monitoring water extraction, well drilling, new water projects, contamination prevention and data sharing [6]. At least five JSETs must be in place in the West Bank, each including at least two members from each side.

Through Oslo II, many allocations have been made. The West Bank is to receive 28.6 MCM/year in water from Israel for domestic use; the remainder is to be taken from the Eastern Mountain Aquifer, including use for new water projects [7]. The divisions of Areas A, B and C were also created. Area A, making up 18% of the West Bank, is fully under Palestinian control. Area B, making up 22% of the West Bank, is under Palestinian control for all but security measures. Area C, which makes up 60% of the West Bank, is under Israel's control [8].

The approval process for water projects in the West Bank is also covered by the Oslo accords. The Palestinian Water Authority submits proposals to the JWC. Technical committees consider the proposal, then send it on to the Israeli Hydrological Services, who considers if Israeli

Fig. 1. Middle-East regional aquifers, showing River Jordan.

water depletion will occur with the project. It then goes back to the JWC. A full committee meets if the proposal is controversial. The entire process has never taken less than 3 months. It is important to note that the JWC has the power of veto [7].

2.3. Main challenges

The regulations set up by the Oslo II accords have caused several controversies, including this power of veto. Israelis have the ability to block any Palestinian water projects with veto power within the JWC [9]. Between 1995 and 2008, approval rates for water projects included 30%–66% for wells, 50%–80% for water supply, and 58% for wastewater [8]. Proposed well locations and supply lines have frequently clashed with plans for new Israeli settlements in the West Bank. Proposals have also gotten vetoed by water office of civil administration after passing the JWC [9]. The division of the West Bank has also caused complications. The region of the West Bank along the Jordan River Basin is in Area *C* [10]. This is also the region with the most fertile lands [11]. Wastewater treatment plants should most strategically be in Area C for land use and watershed purposes. This makes getting approval for water projects very difficult [8]. A number of issues stem from the 70–80 MCM/year of water allocated from the eastern aquifer by Oslo II, considering in 1995, the entire west bank used 118 MCM (s02). Israel uses approximately 82.5% of the abstracted, transboundary groundwater in the West Bank, and one third of Israel's total groundwater use is from the Mountain aquifer [12].

While there are valid criticisms to the Oslo II agreements, there have also been many broader scale positive outcomes, politically and environmentally such as prevention of water quality deterioration. Oslo II has led to official Israeli recognition of water rights in the West Bank. The agreements provide a future for peace building, as it connects the Israeli government with daily contact with JWC water specialists [7]. It delivered the creation of a formal system for West Bank water management, with the promise of new added water quantities, and has been deemed the source of a "new era" of water cooperation [9].

Despite the efforts to improve water quality, water conditions in the Palestinian territories have gotten worse since Oslo II. The Eastern mountain aquifer is now far below that of water levels officially recognized in Oslo II [9]. Additionally, some areas of the West Bank were only brought water every 20–30 d during droughts.

The Israeli minister of the environment and Palestinian minister of water called the JWC ineffective in December of 2011, yet disagreed on how it could be remedied [11]. Many feel that the core issue is that the JWC lacks a platform for settling disagreements. The Israeli government feels as if it is a threat to quality and quantity of Israel's water supply and loss of the country's water control [9]. Some Israelis, however, view the JWC to be effectively proceeding.

Many Palestinians see the JWC as a continuation of Israeli domination. Palestinians lack the ability to veto in area C, Israel has used army forces to stop wastewater treatment, even after JWC approval, and settlements get higher water allocations and are charged at lower rates. A number of projects have been implemented without the approval of the JWC, including farmers drilling unlicensed wells without permits, which the Israeli Defense Forces routinely demolish [8].

Some Palestinians feel there is nothing wrong with Oslo II itself, they just believe they are working with a hostile government. Palestinian water officials have said that the Israeli government tries to destroy projects and agreements [9]. One of the major complaints on the Palestinian end is the slow implementation of projects. Palestinian water specialists have condemned the permitting process due to the few tangible results, delays and high cost of water. Some believe the delays are deliberate in order to sabotage them [7]. JSETs have been criticized due to the extra layer of bureaucracy, and the fact that Palestinian water technicians were now accompanied by Israelis taking data [9].

The calculated 78 MCM/year of water for the West Bank overestimated the remaining potential of the aquifer [9]. Water shortages are leading to overexploitation of groundwater [4]. One study on the impacts of climate change on groundwater in the West Bank suggests that evapotranspiration rates will rise with increasing temperatures, and precipitation rates will continue to decrease in the region, increasing further agricultural demands for water [4]. Desalination has been used in countries with extreme water scarcity, however it tends to be expensive, and is only feasible when it is cost-effective [12]. The difficulties presented by the Oslo II accords make localized desalination of brackish groundwater a reasonable solution for agricultural water use in the West Bank.

3. Training programme

This section describes the design and implementation of the training programme involving international student collaboration. Several authors have recognised that unilateral management of shared resources can be ineffective and generate additional environmental problems, particularly in the case of common pool natural resources [13,14]. Israel, Palestine and Jordan share crucial natural resources including streams, water aquifers, sand dunes and air basins. Therefore, action in one jurisdiction has an inevitable and frequent impact on the other states sharing those same resources. Environmental cooperation between countries in conflict can support a more stable relationship as well as improve environmental well-being [15,16]. The combination of awareness, knowledge, skills and practice are necessary in order to create environmental citizenship and locally engage communities [17]. Therefore, the training course included interacting with such communities with a special emphasis on skill-building and practical applications. It set out to explore solutions to the challenges of trans-boundary water management, depletion and salinization, affecting aquifers in arid regions such as Israel and the Palestinian Authority.

The programme recruited 16 students at the Arava Institute, Israel, and 8 students at Aston University, UK. This was considered a very good rate of update relative to expectations, indicating a good appetite for the course. For example, it was initially only intended to recruit four students at Aston. The initial phase of the training, lasting approximately 10 weeks, covered the design of an off-grid desalination system for use in the village Auja in the West Bank. This involved splitting the cohort into teams of 4 or 5 students. This initial phase was intended to be a training course with relatively structured content. The second phase engaged a smaller number of students in project work, as not all the Arava students were available to continue. A prototype was built initially at Aston University (UK), then at Arava Institute for Environmental Studies in Israel, and at a later stage a system will be installed in the Palestinian farming community of Auja village in the Jordan Valley of the West Bank. The training also included a set of workshops, joint sessions, field trips and internships as described next.

3.1. Workshops, joint weekly classes and field trips

Two workshops were held as part of the initial training course. Workshop 1 was a kick-off workshop at the beginning of the course (October 15–17, 2017), the students were exposed and trained in the following skills: team building, course introduction and overview, introduction to desalination technology, and start of team projects. Workshop 2 was a concluding activity at the end of the course (December 17–18, 2017), the main activity in this workshop was team presentations and recommendations.

Between the kick-off and concluding workshop, the following activities were organised:

3.1.1. Joint weekly sessions

Following the initial workshop, the course was continued by means of joint weekly sessions. Both Arava Institute and Aston University students joined the sessions, which lasted about 1 h each, via an online meeting platform. The initial intention was to provide further introductory material on desalination technology via these sessions; however, this turned out to be practically difficult. Instead, the sessions took the form of a progress update from the students, with the instructors providing feedback and suggestions. The sessions also provided an opportunity for the students to become familiar with each other – as no face-to-face meeting had yet taken place between the Arava- and Aston-based students.

3.1.2. Field trip

16 students from the Arava Institute participated in the field trip to the local community in Auja, they met with two farmers' associations in the town, the first association is located in the southern part of the town, cultivating date trees, vegetables, corn and some fruit trees, this association reported a declining quality of their groundwater. The other association is located closer to the centre of the town, focusing on cultivating date trees with a better quality of groundwater available. The students used the capacity factor analysis (CFA) method to conduct the community appraisal. CFA was first proposed by Professor Garrick Louis and coworkers at the University of Virginia, Charlottesville [18,19] to determine the capacity of a community to provide for itself Municipal Sanitation Services (Drinking Water Supply, Wastewater and Sewage Services, and the Management of Solid Waste). The CFA consists of three consecutive steps: (1) map the capacities to provide a certain service, (2) determine a score for each type of capacity and (3) identify the community capacity assessment. The survey enabled the students to understand the needs of the community and their capacity to run and manage the proposed solution.

In summary, the main findings showed: (i) good local capacity in irrigation and wastewater treatment, including pump maintenance, (ii) little access to solar panels though space was available for these, (iii) a large expenditure (about 25% of farmer income) is spent on electricity, (iv) the electricity supply is reliable, (v) brine disposal is problematic, though one suggestion may be to run a pipeline to a nearby creek, and (vi) 50 m^3/d was sought by one farmer to cover the irrigation deficit, for which he was willing to pay $30,000–$40,000 initial investment, indicating a significant financial capacity.

The trip also involved students in collecting and analysing water and soil samples to be used in the system design. The findings from the field trip were shared and discussed with the Aston University students as part of the joint weekly sessions.

3.2. Internships

Three of the Arava Institute students were selected to continue the program as part of the offered internship. The internship included two components: a one-month visit to the Aston University campus and a three-month hands-on component at the Arava Institute. Given that the Aston students were mostly more experienced in engineering, they were asked to provide a structured training for the visiting students, based on an initial proposal provided by one of the instructors. The first component focused on introducing the students to the Aston University engineering lab, a training in solar energy and in-field water sampling. In the second component, the students worked on the desalination system prototype installation at Aston University. Table 1 shows the outline timetable of the training.

3.3. On-line learning platform

The course utilized an online learning platform for the continuous interaction between the students. Implemented in Basecamp®, the platform provided a forum for discussion and exchange of ideas, a file-sharing space that was used to share designs, water tests results, and community capacity analysis findings. Important events such as the workshops were scheduled in the on-line platform. The platform was particularly helpful for the remote, international interaction.

4. Research and technology development

The project and its collaborations provided the environment for a research project alongside the training. As part of the course, the students reviewed and compared desalination technologies. They went on to select the batch-RO method as the preferred approach. This choice was based on two considerations: (i) the inherent advantages of the approach over conventional continuous flow RO, in terms of energy efficiency and recovery achievable and (ii) the fact that the batch-RO systems had already been developed to a certain level by successive teams of students at Aston University. This prior development meant that certain expertise and resources were already available to develop the system

Table 1
Outline timetable for the Arava Institute students during their visit to Aston University

	Week 1	Week 2	Week 3	Week 4
Monday	Induction and orientation	Team meeting Independent research	Team meeting Training for Aston students	Team meeting Independent research
Tuesday	CAD Training	CAD training Presentation to 3rd year students	CAD training Sourcing for Mark 3 rig	CAD training Sourcing for Mark 3 rig
Wednesday	Microcontroller programming	Microcontroller programming	Microcontroller programming	Microcontroller programming
Thursday	Experimentation Mk2A rig	Experimentation Mk2A rig	Experimentation Mk2A rig	Experimentation Mk2A rig
Friday	Independent research	Company visit 1	Company visit 2	Final workshop and social activity

further. Because of its significance for the project, some background to the batch-RO technology and how the concept has evolved is described next.

4.1. Background to the batch-RO technology

Batch filtration operations have been known since pre-industrial times. An example is the wine press in which grapes are compressed in a basket. Openings in the basket allow the juice to pass through while retaining the skins and seeds of the grapes. Today, several manufacturers of laboratory equipment supply batch filtration cells typically used for separation of small quantities of liquid using modern polymer membranes such as ultrafiltration or reverse osmosis (RO) membranes, instead of a basket. These consist of a jar with a detachable base to house the membrane, a magnetic stirrer to disperse concentration polarisation, and an inlet for compressed air to push liquid through the membrane. In the reverse osmosis application, a semi-permeable membrane is used to filter out salts and dissolved solids from the medium, thus achieving desalination.

In a batch-RO operation, the concentration of saline water in the system is kept spatially uniform and the pressure is increased gradually with time. Further background to this technology may be found in the scientific literature [20–22]. The key feature of the technology is that the pressure and energy can be kept to the bare thermodynamic minimum throughout the separation process. In practice this ideal minimum is never fully achieved due to the presence of thermodynamic irreversibilities. Therefore, one of the pedagogical and research goals of the current project is to quantify and understand the difference between the ideal performance and the one actually observed. Based on this understanding, improvements to the design can be conceptualised, realised and evaluated. The learning process thus consists of four steps repeated iteratively: (i) concrete experience, (ii) observation, (iii) conceptualisation, and (iv) realisation and testing. As such this process corresponds closely to the learning cycle put forward by Kolb [23]. In this case, the learning cycle is motivated by the fact that there is a real social need for the technology being developed, and by the belief that the performance of the technology can be gradually improved towards the ideal goal as determined by the underpinning thermodynamic concepts.

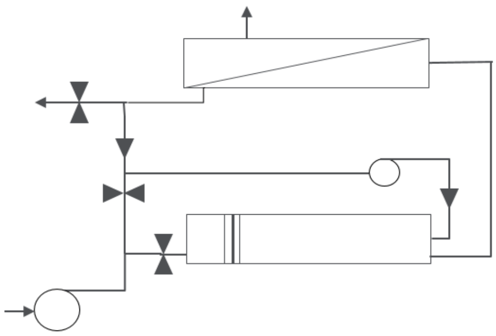
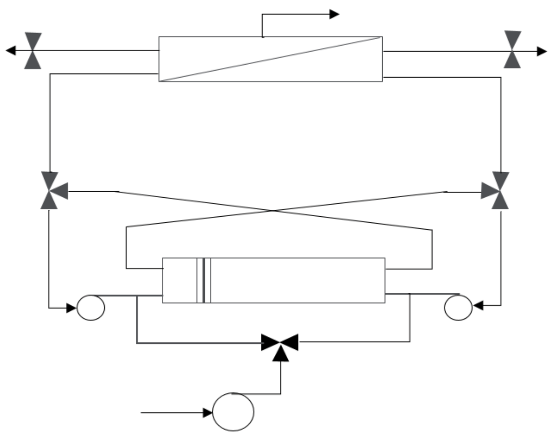
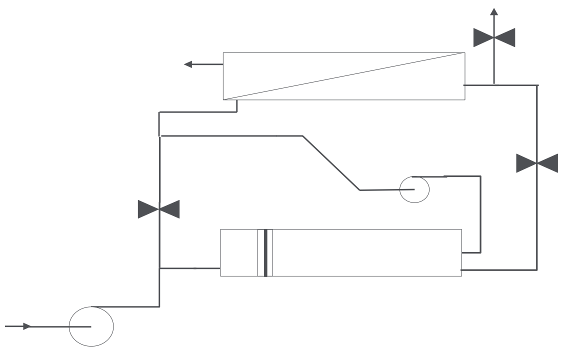
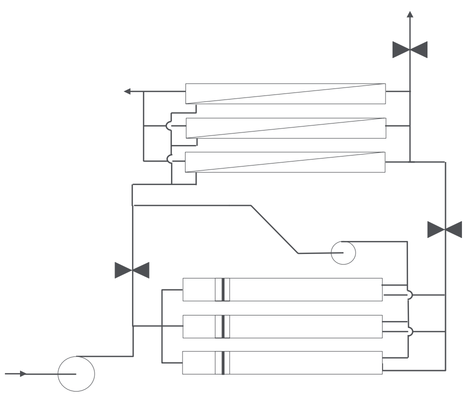
4.2. Evolution of the batch-RO design

Small-scale laboratory filtration cells, as referred to above, do not carry out the filtration at a sufficient rate to supply water for domestic or agricultural applications. Such applications require outputs upward of 1 m^3/d. The output of an RO system is determined largely by the area of membrane used, which in practice needs to be at least several square metres in area. These large areas can be provided by modern configurations such as spiral wound or hollow fibre modules. The approach to the design of the batch-RO system pursued in this project consisted of at least two modules, that is, pressure vessels. The first is used to contain the batch of saline water under pressurisation, and the second is used to contain the spiral wound RO module.

The process of operating the batch RO system is a cyclic one typically consisting of pressurisation, purge and refill stages. During pressurisation, the RO process takes place providing an output of desalinated water. The saline water in the system gradually becomes more concentrated. During purge, the concentrate is flushed out and replaced by feed water at lower salinity. The final refill stage occurs when the batch of saline water is replenished. Some designs allow stages to be carried out simultaneously.

In order to allow the switching between stages, the batch-RO system requires valves. There are several possible ways to configure the valves at the detailed level, each one having certain advantages and disadvantages (Table 2). One of the challenges for the student teams developing this technology is how best to design the system configuration and choose the appropriate types of valves. Related to this, there are considerations about how to control the valves and other elements of the system. The valves and control system introduce additional energy usage, which should be minimised. The reliability, availability and cost of the valves are also important considerations. Further considerations include the possible inclusion of flow reversal in the operating sequence, which may be beneficial to mitigate organic fouling or mineral scaling of the membrane.

Table 2
Schematics of various batch-RO designs showing layouts of valves and recirculation pumps

Version	Name	Schematic	Comments	References
1	Single acting, 3-stage		Baseline design. Uses separate pressurisation, purge and refill stages of operation in sequence.	[24,25]
2	Double acting, 4-stage		Pressurization and refill stages are combined. Follows sequence: (1) pressurisation-refill, (2) purge, (3) pressurisation-refill, (4) purge. Full flow reversal in this configuration may be beneficial to mitigate fouling. The configuration of valves is relatively complex.	[26,27]
3	Single acting, 2-stage		As in version 1, but purge and refill stages are combined to minimise downtime. A short flow reversal time is provided during the purge stage.	[28,29]
4	Single acting, 2-stage, multi-vessel		Similar to version 3 but vessels are triplicated thus increasing the output three-fold.	This paper

Key: non-return valve; 2-port valve; 3-port valve; feed pump; recirculation pump; RO pressure vessel; batch vessel .

4.3. Experiments

Student teams at Aston University have built prototypes according to each of the above configurations (Figs. 2–5). More recently students at the Arava Institute for Environmental Studies in Israel have participated in constructing a prototype according to Version 3. A general feature of the prototypes was the use of standard RO pressure vessels for both the batch vessel and the RO membrane vessel. This reduced cost through use of such standard parts. In fact, the only bespoke part used in any design was the free-moving piston contained in the batch vessel, which was machined from engineering polymer (e.g., acetal) and fitted with an O-ring seal. Fig. 4 illustrates the two Version 3 prototypes each using two standard pressure vessels. Fig. 5 illustrates the Version 4 prototype using in total six standard pressure vessels.

It was important to be able to detect when the piston had reached the end of travel so that the next stage of the desalination cycle could be initiated. In Version 3, proximity sensors were used to detect the end-of-travel position of the piston. However, in other prototypes flow sensors and pressure sensors have also been used to detect end of travel.

The machines have been tested with salinities in the range 0–5,000 ppm of sodium chloride. Test solutions were made up with tap water and culinary grade sodium chloride. Sodium meta-bisulphite was added to neutralise chlorine in the tap water that would otherwise damage the membrane. Further experimental details may be found elsewhere [24,27–29]. The prototypes were evaluated for output (m^3/d), recovery ratio, salt rejection and specific energy consumption (SEC in kWh/m^3). SEC was evaluated based on (a) the hydraulic work done by the feed-pump and (b) total electrical energy supplied to the rig. The former gave a lower value, as it did not include energy consumption by the recirculation pump, or any losses associated with the feed-pump. For reference, we also calculated the ideal thermodynamic minimum SEC as follows:

$$\mathrm{SEC} = P_{\mathrm{osm}}\left(\frac{1}{r}\right)\ln\left[\frac{1}{(1-r)}\right] \tag{1}$$

where P_{osm} is the osmotic pressure of the feed solution and r is the recovery ratio achieved.

As equipment was improved and modified, experimental conditions changed. For example, one of the recent changes was the use of an improved feed pump for more efficient

Fig. 2. Version 1 prototype: single-acting batch-RO system with manually operated valves, at Aston University, UK.

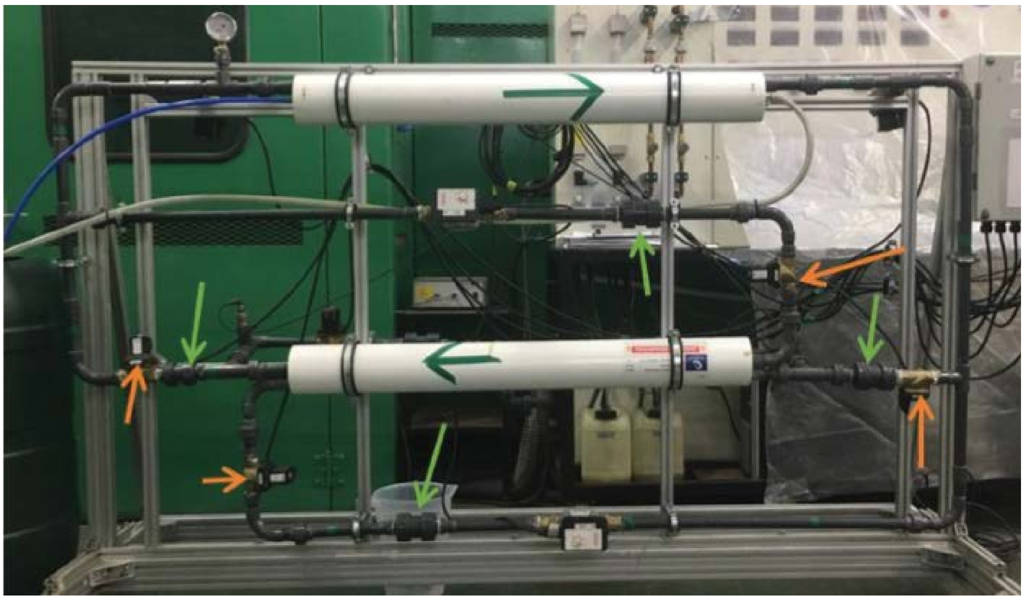


Fig. 3. Version 2 prototype: single-acting batch-RO system with electrically operated valves, at Aston University, UK. Yellow arrows indicate solenoid valves and green arrows indicate non-return valves.

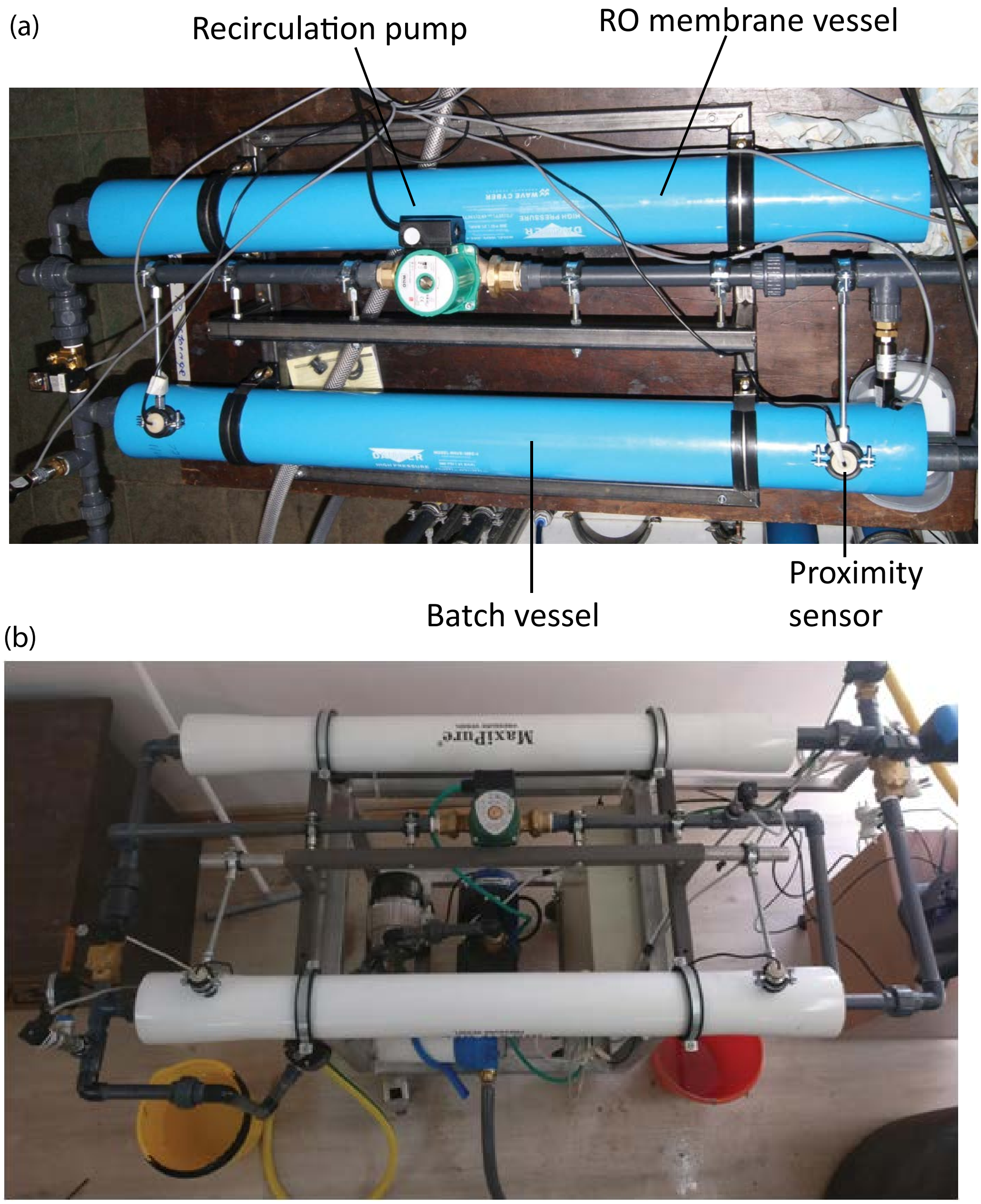


Fig. 4. Version 3 prototypes of the batch-RO system, each using two identical pressure vessels, one to contain the RO membrane and the other to contain the batch of feed water; (a) at Aston University, UK and (b) at Arava Institute of Environmental Studies, Israel.

operation. Whereas the first prototype used only manual valves, automated valves were used from Version 2 onward and the corresponding measurements of SEC included the power used for the valves.

5. Results and discussion

5.1. Experimental results

Table 3 summarises the results obtained with the different prototypes. As seen, the SEC most recently obtained was 1.3 kWh/m^3, which is somewhat above the target of 1 kWh/m^3. A breakdown of SEC showed that about 67% was used by the feed pump, and 33% by the other loads, that is, the recirculation pump and solenoid valves. In this case, the recovery ratio was 55% which is below the target of 70%. The recovery ratio was here limited to 55% to ensure satisfactory flushing of the RO modules during the purge phase; however, this is being examined to reduce the purge phase time thus improving recovery and also reducing SEC and increasing output. In all cases, there is a large difference between hydraulic and electrical work, indicating significant scope to improve efficiency of the feed pump.

Work is now in progress to characterise further and optimise the Version 4 prototype as well as to simplify aspects of priming and shutting down the machine. There are also

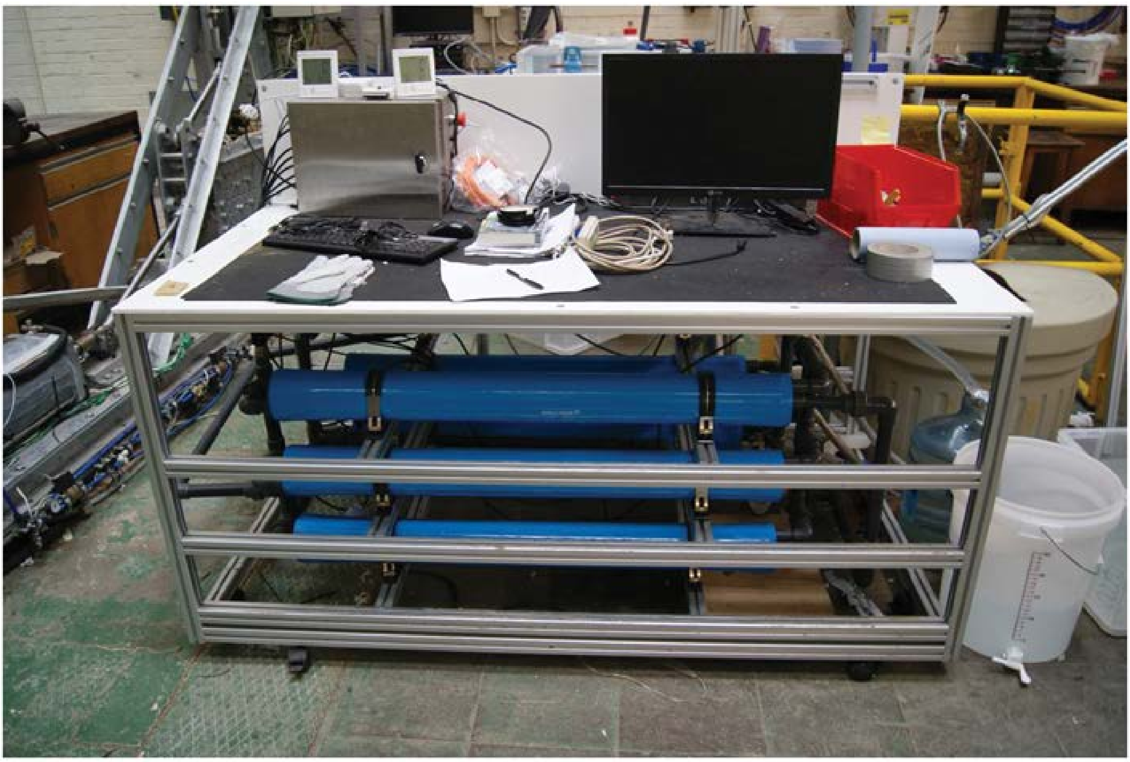


Fig. 5. Version 4 of the batch-RO prototype giving increased output through use of multiple vessels, at Aston University.

Table 3
Results with 2,000 ppm feed salinity. Note osmotic pressure P_{osm} = 154 kPa

	Version 1	Version 2	Version 3	Version 4
Type	Single-acting 3-stage	Double-acting	Single-acting 2-stage	Single-acting 2-stage multi-vessel
Control	Manual	Automatic	Automatic	Automatic
Recovery (%)	70	76	73	72
SEC ideal minimum (kWh/m^3)	0.074	0.080	0.077	0.076
SEC hydraulic (kWh/m^3)	0.27	0.19	0.36	0.2
SEC electrical (kWh/m^3)	Not measured	2.62	2.31	1.26
Rejection (%)	88	80.5	95	90
Output m^3/d	Not measured	1.32	2.86	3.76
References	[24,25]	[26,27]	[28,29]	This paper (preliminary)

on-going challenges associated with reduction of costs, including cost-effective design of valves and of the support frame structure.

5.2. Feedback and reflections

Overall feedback from the participating students was gathered by means of questionnaires and analysed. Students tended to appreciate the opportunity for international cooperation, the practicality of a real-world issue, and the interdisciplinary nature of the project. They enjoyed the cross-cultural interactions and the opportunities for teamwork, international travel and fieldwork. Areas for improvement included having clearer, fixed goals and sharper definition of project scope and resources from the beginning.

The varied background experience and of the students made it somewhat challenging to design the content and level to suit all. Some students had yet to embark on university education; while others were already graduates. These disparities were also reflected in their responses to the problem-led nature of the course design. This generally appealed to the more experienced students, whereas less experienced students may have preferred a more content-led approach with greater predefined structure. Some students felt that more time should have been spent on fundamental aspects of desalination. These considerations will be taken into account to design future course elements that can be selected to suit the level and expectations of learners.

6. Conclusions

The Jordan River Basin is, by its transboundary nature, a problematic area in terms of water management for agriculture. The Oslo II agreements limit the Palestinians living in the West Bank in terms of availability of and access to groundwater, leading to over-pumping and an increase in salinity. The designated water allocations are inappropriate for the current trends of decreasing water quantity and increasing groundwater salinity, making the Palestinians in the West Bank a prime candidate for use of high-recovery desalination technologies. Desalination can be energy intensive, and therefore costly; so the motive of this project was to design an off-grid desalination system powered by solar energy. The main findings from the project so far have been, as regards the training objectives:

- It has been possible to convene an international team of students to collaborate in a meaningful way, initially remotely and then through visits and face-to-face interactions. The students were able to build functioning prototypes of high-recovery desalination technologies based on a batch-RO process.
- The students and other participants in the projects represented citizens and stakeholders from different territories overlying the transboundary water resources. Despite the controversies surrounding the Oslo accords governing such resources, no difficulty was observed in forming a harmonious international team.
- The design instructions and results have been incorporated in a number of reports produced by the students through their project work.

As regards the research objectives:

- The low SEC (<1.3 kWh/m^3) obtained is favourable for use in solar energy application. The pumps used in the system are adapted for use with solar PV power. However, the system has not yet been implemented with a PV array as such.
- Recovery ratio has been measured in the range 70%–76%, in line with the initial aim of 75%.
- Output rate of 3.76 m^3 per 24 h period has been achieved, meeting the initial objective of 2–4 m^3/d.
- The parts used have been mainly off-the-shelf, the one exception being the piston used in the batch vessel, which was machined from acetal using a lathe.

Aspects of learning from the project, will also be useful in future implementations:

- The importance of adjusting the content and approach of the course to meet the varying expectations of learners.
- For a good student experience, attention should be paid to ensuring sufficient resources to support the course – both instructor time and high-quality learning resources.

In summary, the project has demonstrated a successful but localised example of transboundary water cooperation at the institutional and student level. The feedback and experience from the training course will enable it to be improved in future for the benefit of those participating. Based on the enthusiastic uptake by students, the progress made in the training and community engagement aspects, and the technological advancements achieved, it is recommended that this type of research-led training project be repeated and developed further. Members of the European Desalination Society can contribute to the development and delivery of on-line learning resources for use in such projects. Free access to learning resources could do much to spread desalination technology and foster collaboration across borders. The approach described here may be applied, not only in Jordan Valley but also in other regions where transboundary water resources are increasingly depleted and affected by salinization.

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